IJIST
P ISSN : 2618-1630
E ISSN : 2909-6130
Recognized Journal

MODIS-observed spatiotemporal changes in surface albedo of Karakoram glaciers during 2000-2018

Original Article

Zaeem Hassan Akhter[1,2,3], Chang-Qing Ke[1,4,5], Irfan Ahmed Soomro[1,2,3], Asma Amir[6]
[1] School of Geography and Ocean Science, Nanjing University, Nanjing, China
[2] Jiangsu Provincial Key Laboratory of Geographic Information Science and Technology, Nanjing University, Nanjing, China
[3] Key Laboratory for Satellite Mapping Technology and Applications of State Administration of Surveying, Mapping and Geoinformation of China, Nanjing University, Nanjing, China
[4] Collaborative Innovation Center of Novel Software Technology and Industrialization, Nanjing, China
[5] Collaborative Innovation Center of South China Sea Studies, Nanjing, China
[6] School of Geographical Science, Northeast Normal University, Changchun, China
* **Correspondence:** Zaeem Hassan Akhter, Email: zaeem@smail.nju.edu.cn

Citation | Akhter. Z. H, Ke. C. Q, Soomro. I. A, Amir. A, "MODIS-observed spatiotemporal changes in surface albedo of Karakoram glaciers during 2000-2018". International Journal of Innovations in Science and Technology. Vol 4, Issue 1, 2022, pp: 246-265.
Received | March 04, 2022; **Revised |** March 07, 2022 **Accepted |** March 08, 2022; **Published |** March 09, 2022.

The role of albedo is very important in modulating the surface energy balance of glaciers. The main objective of this study is to assess the spatiotemporal variability in surface albedo of the Karakoram glaciers in Pakistan during the summer seasons (June, July and August) for the period from 2000-2018. We used Moderate Resolution Imaging Spectroradiometer (MODIS) data to estimate the amount of glacier surface albedo. We combined the MODIS Terra- and Aqua-derived albedo products to reduce the amount of cloud influence and to improve the estimation of glacier surface albedo. Our results indicate that the average annual decrease in albedo is ~0.041% during the summer. The decrease in albedo was relatively high during recent years, with an annual rate of decrease of ~0.45%. The decreasing trend in albedo is towards the north-western part of the Karakoram mountain range. Climate change is the potential cause of albedo variations in the study area. Albedo has a strong negative correlation with temperature (r = -0.811) and a strong positive correlation with precipitation (r = 0.809). The present study concludes that the trend in decreasing albedo is higher during the recent years than the last decade and climate change is playing a vital role in it.

Keywords: 1; MODIS 2; surface albedo 3; glacier 4; climate factors 5; Karakoram.

Author's Contribution. Z.H.A: data analysis and write-up; C.Q.K: supervision; I.A.S: data processing, A.A: data collection

Acknowledgement. Authors would like to acknowledge National Snow and Ice Data Center (http://nsidc.org) from where the MODIS snow data used in this study was obtained and Pakistan Meteorological Department (PMD) for providing climate data.

Conflict of interest. Authors declare no conflict of interest for publishing this manuscript in IJIST.

IPIndexing Indexing Portal
CiteFactor Academic Scientific Journals
RESEARCHBIB ACADEMIC RESOURCE INDEX
IDEAS
Scientific Journal Impact Factor TOGETHER WE REACH THE GOAL
JOURNALS MASTER LIST
ROOTINDEXING JOURNAL ABSTRACTING AND INDEXING SERVICE
Scilit
INFOBASE INDEX

INTRODUCTION

In the recent time, global climate change has become one of the most widespread topics in government, industry and research in general. The interest towards the global climate change has increased significantly since the mid-20th century. Climate change is leaving a negative impression on the world's glaciers causing a decrease in glacial landmass. Some scientists think that the glaciers in the Himalaya region are retreating very fast and it is also predicted that the glaciers in the region can be virtually disappeared by 2035 [1, 2, 3]. This is need of time to conduct studies to understand the main causes of retreating glaciers.

According to the recent inventories [4], the Karakoram region consists of roughly more than 13,500 glaciers which covered an area of about 22,800km^2 It is estimated that the total volume of the glacial ice in the region is about 2,200km^3 which is about more than 30% of the total volume of High Mountains of Asia [5]. The snowmelt and runoff from the glaciers, all together is the key source of water for the rivers in the region [6]. It makes the glaciers in the Karakoram region prodigious importance in contributing water supply for millions of the people downstream [7]. Due to the increase in the summer melt at Karakoram glacial region, stream flows are declining from the highly glaciated Indus tributaries with implications for highly dense Indus Plains population [8].

Warren [9] defined Albedo (α) as the ratio of incoming to outgoing radiations, and considered the measure of surface reflectivity. The term albedo refers to the amount of solar radiation reflected by a surface. Fresh snow can reflect more than 85% of sunlight, which makes it among the highest reflective substances occurring in nature. Under warm conditions, the amount of snow albedo can be reduced to less than 65% in the presence of water as the snow crystals become metamorphosed. Snow albedo can be reduced to below 30% in the presence of impurities such as black carbon, dust or microbes, which means that impurity-rich bare glacier ice absorbs more sunlight and lessens albedo by almost a factor of three [10].

Land surface albedo is an important climate variable that defines the amount of incident solar irradiance reflected by the surface of the earth [11], which is an important geophysical parameter for controlling the energy budget in the atmosphere-land interaction [12]. It is the basic component of the surface energy balance of the glaciers [13], having a significant impact on the surface net radiation and plays a vital role in regional and global climate modelling [14]. The availability of energy for ablation is governed by the spatiotemporal albedo variability for snow and ice surfaces [15], which is dramatically affected by the presence and condition of the snow [16]. The surface energy balance is determined by the variables of snow albedo, snow cover duration and snow cover extent influencing the glacier mass balance [17].

A research conducted by Wang*, et al.* [18] demonstrates the spatial and temporal variation of surface albedo during the year 2000-2011 on western China region. They used Landsat TM/ETM+ data as well as MODIS data to estimate the surface albedo of the nine glaciers in the study region. According to their research, the amount of albedo has gentle variation on the tongue of a single glacier with the change of altitude, there is a rapid increase in albedo as moving towards the middle part of the glacier while the albedo values fluctuate in the accumulation zone of a single glacier.

Brock*, et al.* [19] conducted a study on the Haut Glacier d'Arolla in Switzerland to describe the spatiotemporal changes in the surface albedo during the ablation season of year 1993 and 1994 using ground measurements. They correlated the surface albedo measurements

with meteorological data to explain their relationship and it was the first attempt to its nature monitoring the albedo of whole glacier throughout the ablation season. A research about the glacial albedo change was proposed by Fugazza*, et al.* [20] using Landsat data available from 1984 to 2011. The study was conducted on the fifteen selected glaciers in Central Alps region to determine the magnitude of change in glaciers albedo. The study confirmed that there was decrease in the albedo on 14 glaciers out of all 15 glaciers significant at 95% confidence level. The decrease in the rate of albedo ranged between 0.001 and 0.006 per year with an average decrease rate of 0.003 per year.

A research was conducted at Johnsons Glacier to investigate the albedo trend and seasonality by using MODIS daily snow albedo product (MOD10A1). MODIS data from the month of December 2006 to February 2015 was used in the study for all sky conditions. The overall amount of albedo increase was observed 2% for in-situ measurements and 6% for MODIS-derived albedo measurement during the period 2006-2015 [21]. The spatial and temporal changes over snow surface area can be determined with the help of accurate measurements of spectral snow albedo obtained from the satellite data. To measure the spectral snow albedo, a study was conducted in the northern areas of Pakistan by using Landsat TM and ETM+ spatiotemporal imagery datasets. The results showed a decreasing albedo amount of about 0.058 in the recent year (2000) as compared to the older surface albedo data (1992) [22].

There are some primary and secondary objectives of the research conducted to measure surface albedo variability of the Karakoram region. The primary goal of this study is to understand the behavior of spatial and temporal variation in the glacial albedo and its response to climate change in the Karakoram region. In recent times, there have been a lot of researches on the albedo change on different glaciers around the world. It has been noticed since the past few decades that the variation in the albedo have caused a huge impact on the global climate change. The main objectives of the present study are:

- To assess the spatial and temporal variability of surface albedo on the glaciers in the Karakoram region of Pakistan using MODIS-derived (MOD10A1) data
- To analyze the surface albedo variation on every single glacier of each year from 2000-2018 during the summer season (June, July, August)
- Comparing the surface albedo variation with elevation using ASTER digital elevation model (DEM) data by dividing study area in six elevation zones
- Discussing the factors playing an important role in controlling surface albedo variation in the study area

Material and Methods.

Investigation site. The Karakoram range of mountains is located at approximately 36°N and 74°E, spanning parts of Pakistan (Gilgit-Baltistan), China (Xinjiang), India (Ladakh) and containing the largest concentration of glaciers outside the polar regions [23]. This system of mountains extending approximately 500 km in length between Central and South Asia is a complex range of mountains that includes the Himalayas to the southeast, the Kunlun Mountains to the northeast, the Pamir Mountains to the northwest and the Hindu Kush to the west.

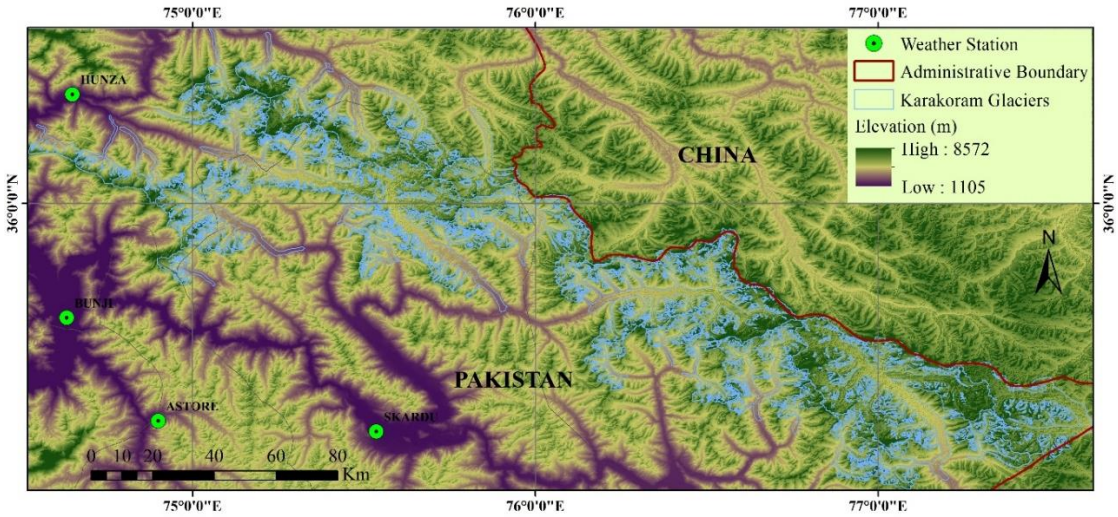

Figure 1. Map of the study area showing the elevation in metres and the Karakoram region under study area highlighted with the light blue colour.

Table 1. Details of the 27 glaciers under study [24]

Name of Glacier	CenLon (deg)	CenLat (deg)	Area (km^2)	Zmin (m)	Zmax (m)	Zmed (m)	Slope (deg)	Lmax (m)
Baltoro Glacier	76.41	35.74	809.11	3385	8569	5393	23.80	63448
Barpu Glacier	74.82	36.06	105.04	2810	7432	5093	22.30	29588
Biafo Glacier	75.59	36.01	559.81	3045	7148	5043	19.40	67807
Bilafond Glacier	76.94	35.21	132.55	3840	7112	5368	23.30	21762
Braldu Glacier	75.77	36.04	175.98	3990	6461	5195	20.00	35951
Bualtar Glacier	74.69	36.09	68.38	2271	7235	4868	27.60	25082
Chogo Glacier	75.22	35.87	295.32	2769	7008	4855	22.50	47345
Chogolisa Glacier	76.46	35.43	83.15	3533	7209	5150	24.90	19568
Ghandogoro Glacier	76.36	35.58	66.13	3476	7050	5090	22.10	21564
Gharesa Glacier	74.98	36.25	78.01	3825	7523	5542	28.70	21541
Hispar Glacier	75.28	36.05	495.65	3110	7794	4854	23.30	54453
Khurdopin Glacier	75.44	36.19	203.34	3314	7718	5391	23.60	31640
Kondus Glacier	76.66	35.44	256.15	3257	7540	5120	22.80	40801
Kutiah Glacier	74.94	35.81	50.95	2851	7353	5106	26.80	19316
Lokpar/Aling Glacier	76.22	35.55	56.25	3649	6432	5084	24.20	18141
Minapin Glacier	74.59	36.16	56.07	2541	7178	4346	26.70	18834
Momhil Glacier	75.15	36.32	73.26	2881	7506	5630	29.30	30252
Mulungutti Glacier	75.21	36.34	97.75	2911	7799	5664	26.90	23889
North Terong Glacier	77.34	35.31	117.05	3980	7334	5666	23.20	21319
Panmah Glacier	75.95	35.85	334.68	3516	7054	5084	20.10	33298
Rimo Glacier	77.43	35.29	439.62	4921	7290	5685	16.20	46263
Sherpikang Glacier	76.81	35.42	65.82	3576	7288	5458	21.00	19927
Siachen Glacier	76.89	35.43	1077.95	3596	7579	5518	20.10	76288

Soiu Glacier	75.54	35.95	59.80	3364	6300	4582	23.00	15601
Sosoun Glacier	75.55	35.84	74.25	3680	6390	4551	19.50	16465
Virjerab Glacier	75.65	36.15	167.43	3592	6368	5241	23.10	40178
Yazgil Glacier	75.31	36.24	133.75	3234	7709	5910	24.40	31403

Note: CenLon and CenLat are the longitude and latitude (in degrees), respectively, of a single point representing the location of the glacier; the area (Area) of the glacier is in km^2, calculated in Cartesian coordinates on a cylindrical equal-area projection of the authalic sphere of the WGS84 ellipsoid, or, for nominal glaciers, accepted from the source inventory; Zmin and Zmax are the minimum and maximum elevations (meters above sea level) of the glacier, obtained in most cases directly from a DEM covering the glacier; Zmed is the median elevation (m) of the glacier, chosen by sorting the elevations of the DEM cells covering the glacier and recording the 50th percentile of their cumulative frequency distribution; Slope is the mean slope of the glacier surface (deg), obtained by averaging single-cell slopes from the DEM; and Lmax is the length (m) of the longest surface flowline of the glacier. The length is measured according to the algorithm proposed by Machguth and Huss [25].

In this study, we analyzed the part of Karakoram located in Pakistan (Figure 1; Table 1). Siachen Glacier is the largest glacier in the region, with an area of approximately 1078 km^2, and is the largest glacier outside the Arctic region. The Karakoram exhibits heavy glaciation because of the great elevation, especially on the more humid southern slopes. The inventory suggests that the total number of glaciers in the Karakoram area may exceed 7000, which consists of approximately half of the glacierized area surveyed on earth. The Indus River in Pakistan and the Yarkand River in Xinjiang Province, China, are fed by the glaciers of the Karakoram as a watershed, variously estimated at between 18,000 and 20,000 km^2 [26]. The Karakoram glacial region is the most glaciated area outside the polar region consisting of some longest glaciers in the world (i.e. Siachen glacier 76km – World second longest glacier outside the polar region, Biafo glacier 67km – third longest glacier in the World outside the polar region) [27].

MODIS Daily Snow Product (MOD10A1/MYD10A1). MOD10A1 is a daily MODIS (Terra-derived) snow product containing NDSI snow cover and daily albedo products from 1999 to the present. The National Snow and Ice Data Center (NSIDC) processes and distributes the MODIS (MOD10A1) Snow Cover and Snow Albedo Daily L3 Global 500 m SIN Grid, which is available at https://nsidc.org/data/mod10a1 [28]. The MOD10A1 product provides an estimation of daily blue-sky albedo, corresponding to broadband albedo at a resolution of 500 m [29]. This albedo product is stored in the form of integer values ranging between 0 to 100 (percent) and the accompanying the quality control flags [30]. MYD10A1 is daily MODIS (Aqua-derived) snow product containing NDSI snow cover and daily snow albedo products from 2002 to the present. The Earth Observation System satellite aqua is also known as EOS PM-1, which passes in the afternoon from south to north over the equator completing an orbit around the Earth every 1-2 days.

Climate data. The study area lies in the Gilgit-Baltistan territory of Pakistan situated in the northern part of Pakistan. The weather station data of four weather stations (Astore, Gilgit, Hunza and Skardu) in Gilgit-Baltistan were obtained from the Pakistan Meteorological Department (PMD) (Table 2). The weather station data were later corrected with the remote

sensing data obtained from MODIS to generate a relationship between the ground-based weather station (meteorological) data and remote sensing data.

Table 2. Weather stations near the Karakoram glacial region

		Geographic Location	
Weather Station	Elevation (m)	Latitude	Longitude
Astore	2168 m	35° 22' 1" N	74° 54' 0" E
Bunji	1372 m	35° 40' 1.2" N	74° 37' 58.8" E
Hunza	2156 m	36° 19' 1" N	74° 39' 0" E
Skardu	2317 m	35° 20' 10" N	75° 32' 10" E

Digital Elevation Model (DEM) data. The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) onboard the National Aeronautics and Space Administration (NASA) spacecraft Terra was released in mid-October 2011, covering a land surface between 83°N to 83°S, is capable of collecting in-track stereo images using nadir-and aft-looking near-infrared cameras. Version 2 of the ASTER Global Digital Elevation Model (GDEM) is comprised of 22,702 1° x 1° tiles with an overall accuracy of ~17 m at a confidence level of 95%. In this study Karakoram was divided into 6 elevation zones and later compared it with the MODIS albedo product.

MODIS Data Processing Scheme.

MOD10A1 and MYD10A1 are tiles of daily level-3 global snow cover product at a spatial resolution of 500m selected from a best observation obtained from the multiple observations of MODIS MOD10_L2G and MYD10_L2G product. M (O, Y) D10A1 contains the best observation of the day for NDSI daily snow cover product and snow albedo product. The study area is located in the MODIS tile h24v05, only the MODIS daily snow albedo was extracted from the M (O, Y) D10A1 product for further analysis. The study was conducted on 27 glaciers in the study area. The research area was analysed as a whole as well the analysis was performed on every single glacier in the Karakoram glacier region of Pakistan. Only the summer months (June, July, August) data was used in the research to analyse the spatial and temporal variation of glacial albedo in the study area. MODIS Reprojection Tool (MRT), MATLAB and ArcGIS version 10.8 for spatiotemporal analysis of albedo in the study region and SPSS and Origin software were used to perform statistical analysis.

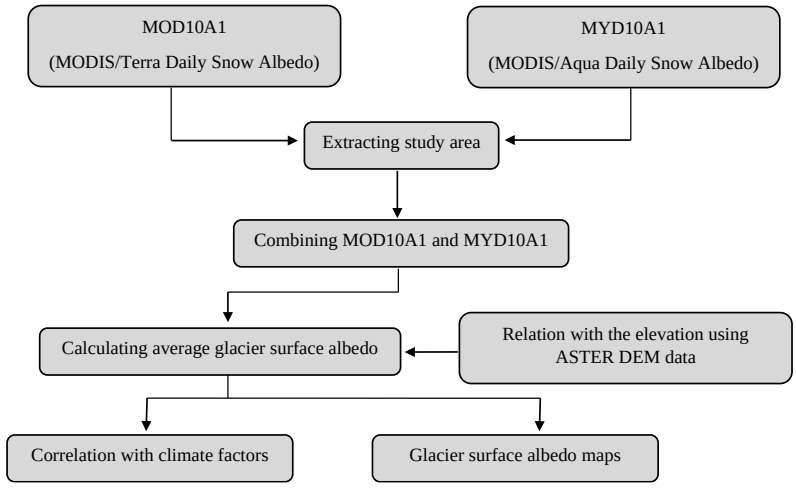

Figure 2. Flow chart of the methodology used for extracting and processing the MODIS albedo data to measure the change in the glacier surface albedo

Cloud Elimination

A simple technique to eliminate cloud cover from a dataset is by combining MODIS Terra-and Aqua-derived products. Xie, *et al.* [31] generated the combined product of MOD10A1 and MYD10A1 to eliminate the cloud effect and to improve the quality of the results by decreasing the amount of cloud cover by ~10% compared to the MODIS Terra/Aqua products alone.

Table 3. Cloud elimination by combining MODIS Aqua and Terra products

		Total	MODIS Terra Albedo (MOD)	MODIS Aqua Albedo (MYD)	After Cloud Elimination (MOD+MYD)
August 2, 2010	No. of Pixels	3775	2522	2454	2745
			66.80 %	65.01 %	72.71 %
	Cloud Pixels		1128	929	502
			29.88 %	24.61 %	13.29 %
August 19, 2008	No. of Pixels	3775	2438	1943	2469
			64.58 %	51.47 %	65.40 %
	Cloud Pixels		853	1106	538
			22.60 %	29.30 %	14.25 %
August 2, 2006	No. of Pixels	3775	2751	2844	3095
			72.87 %	75.34 %	81.98 %
	Cloud Pixels		418	252	91
			10.07 %	6.67 %	2.41 %

For instance, on August 2, 2010, the data obtained from the MODIS Terra satellite (MOD10A1) was approximately 29.88% clouds at the Baltoro Glacier, and the data obtained from the MODIS Aqua satellite (MYD10A1) contained 24.61% clouds at the Baltoro Glacier. When we combined both the Aqua and Terra products, the cloud cover was reduced to 13.29%. By using this simple technique, approximately 55.50% of the clouds were removed. The number of pixels containing snow was also improved by combining the MOD10A1 and MYD10A1 images. Similarly, on August 9, 2008, the data obtained from Terra contained 22.60% clouds, and data obtained from Aqua contained 29.30% cloud cover. The cloud cover was reduced to 14.25% by combining the Aqua- and Terra-derived products (Table 3).

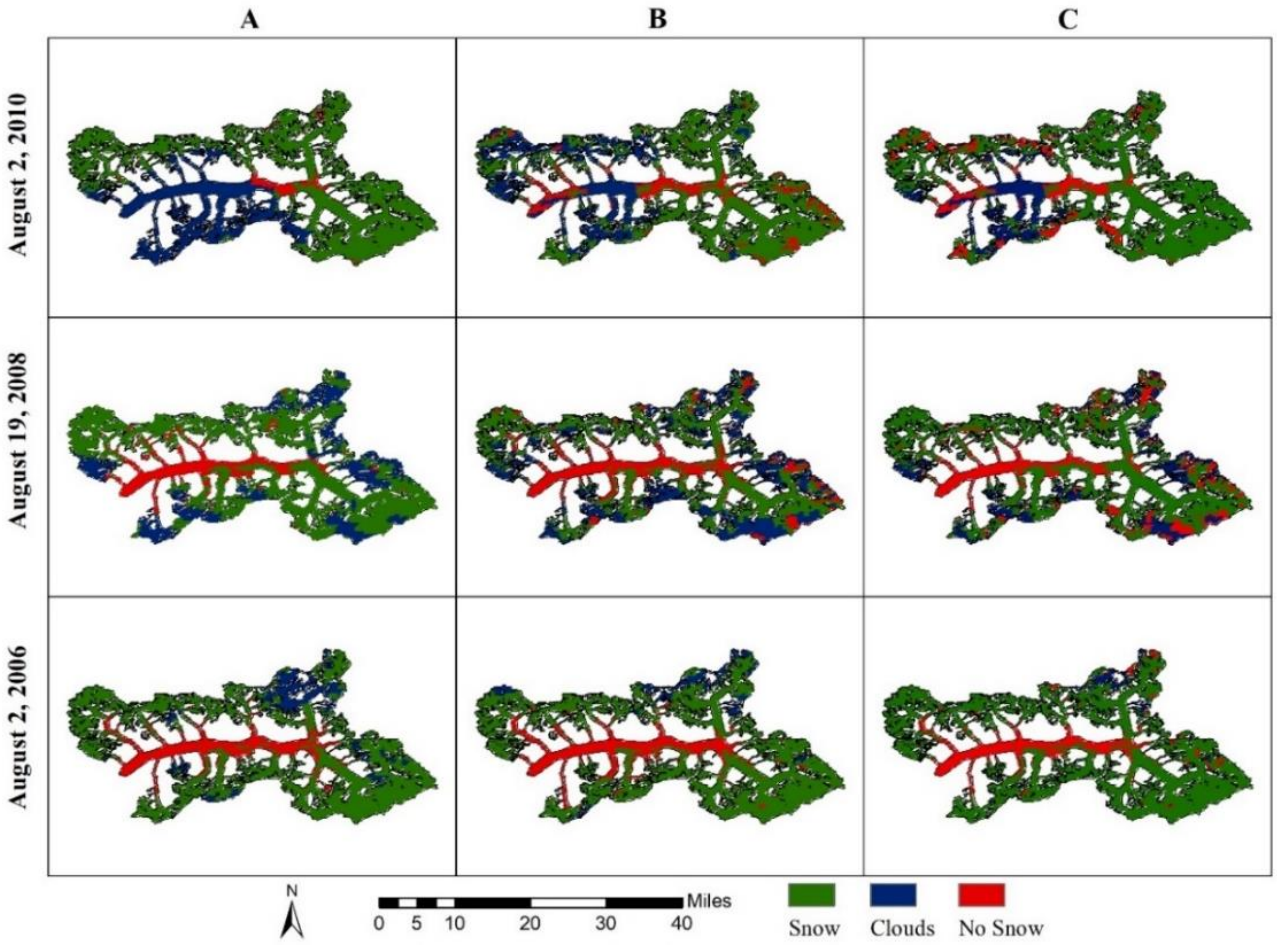

Figure 3. Combined Terra- and Aqua-derived albedo product obtained on August 2, 2010, at Baltoro Glacier. (A) MODIS Terra albedo (B) MODIS Aqua albedo (C) Combined MODIS Terra and Aqua albedo product

The snow area was 72.87% in the MODIS Terra product and 75.34% in the MODIS Aqua product before combining the MODIS Terra and Aqua products. The quality of the snow area improved to 81.98% by combining both products. In total, 10.07% and 6.67% of the areas in the MODIS Terra and Aqua products, respectively, contained clouds, which improved to just 2.41% by combining both products (Figure 3).

Results and discussion.

Glacier surface albedo variations. To analyse the variation in the glacier surface albedo, we calculated the means of glacial albedo over the Karakoram mountain range during the summer seasons and observed the variation trends over 2000-2018 (Figure 4). The average albedo during June, July and August (the summer months) was calculated from 2000 to 2018. Least squares regression was used to estimate the trends to determine the best linear fit for the data. There was a very slight decreasing trend at an average rate of 0.41% per decade during the summer seasons of 2000 to 2018 (Figure 5).

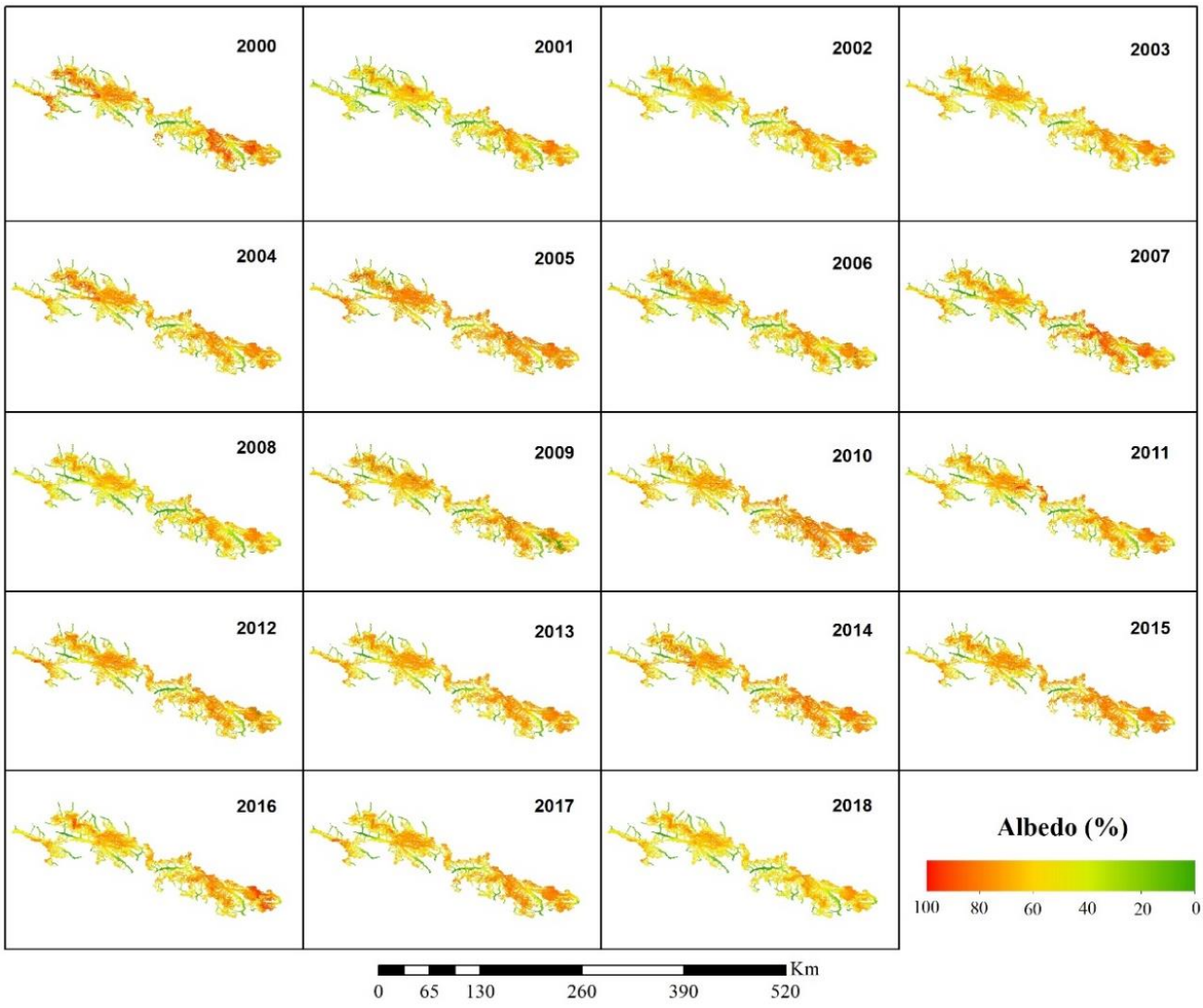

Figure 4. MODIS-observed surface albedo of the Karakoram glaciers from 2000 to 2018

The interannual variation was between 52.82% and 42.85%, and the average amount of albedo was 46.82% during the summer seasons of 2000 to 2018. The highest albedo was 52.82% during 2005, and the lowest albedo was 42.85% during 2008. The rate of decrease in albedo was very fast in recent years compared to the decrease in albedo in the past decade. During the past decade (2000-2009), the trend was slightly flat and in the negative direction, with a slight decrease in the rate of albedo estimated to be 0.12% per year (Figure 6). The decreasing trend in albedo was slightly sharp, with an average rate of decrease of 0.45% per year (Figure 6) during recent years (2010-2018). Out of the 27 glaciers under study, most of the glaciers showed a very small decrease in albedo, and some glaciers with an increasing trend since 2000 had a decrease in albedo during the last decade.

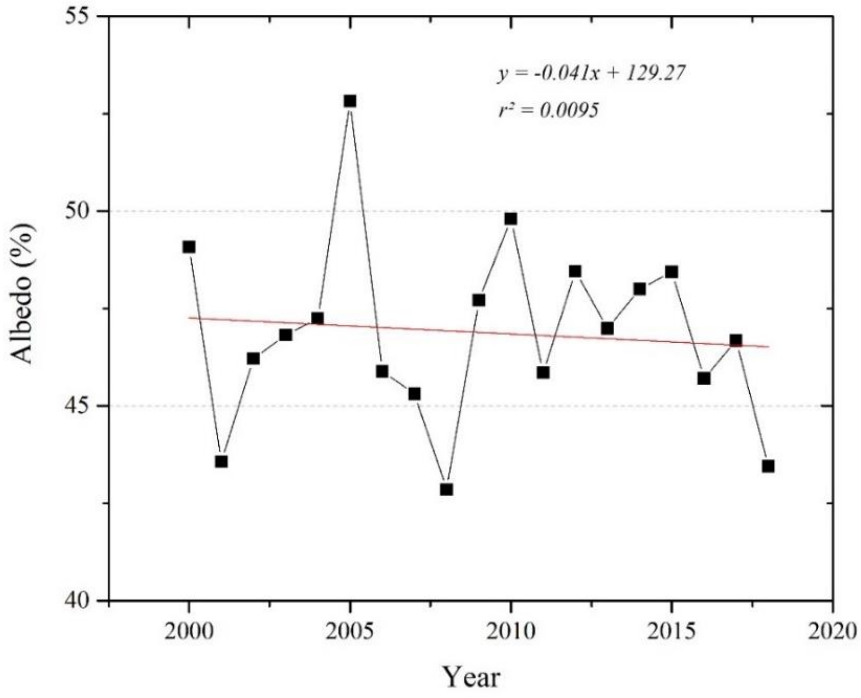

Figure 5. Surface albedo variation in Karakoram glaciers during the summer seasons of 2000 to 2018. The red line shows the trend of decreasing surface glacier albedo

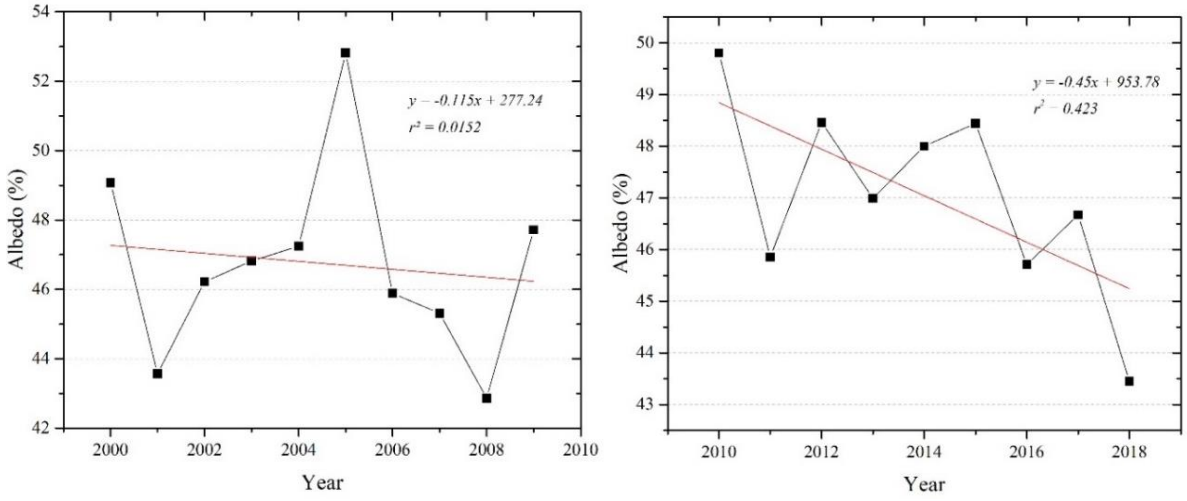

Figure 6. Average snow albedo variations over the past two decades show that the rate of change in albedo is nominal from 2000-2009 compared to 2010-2018.

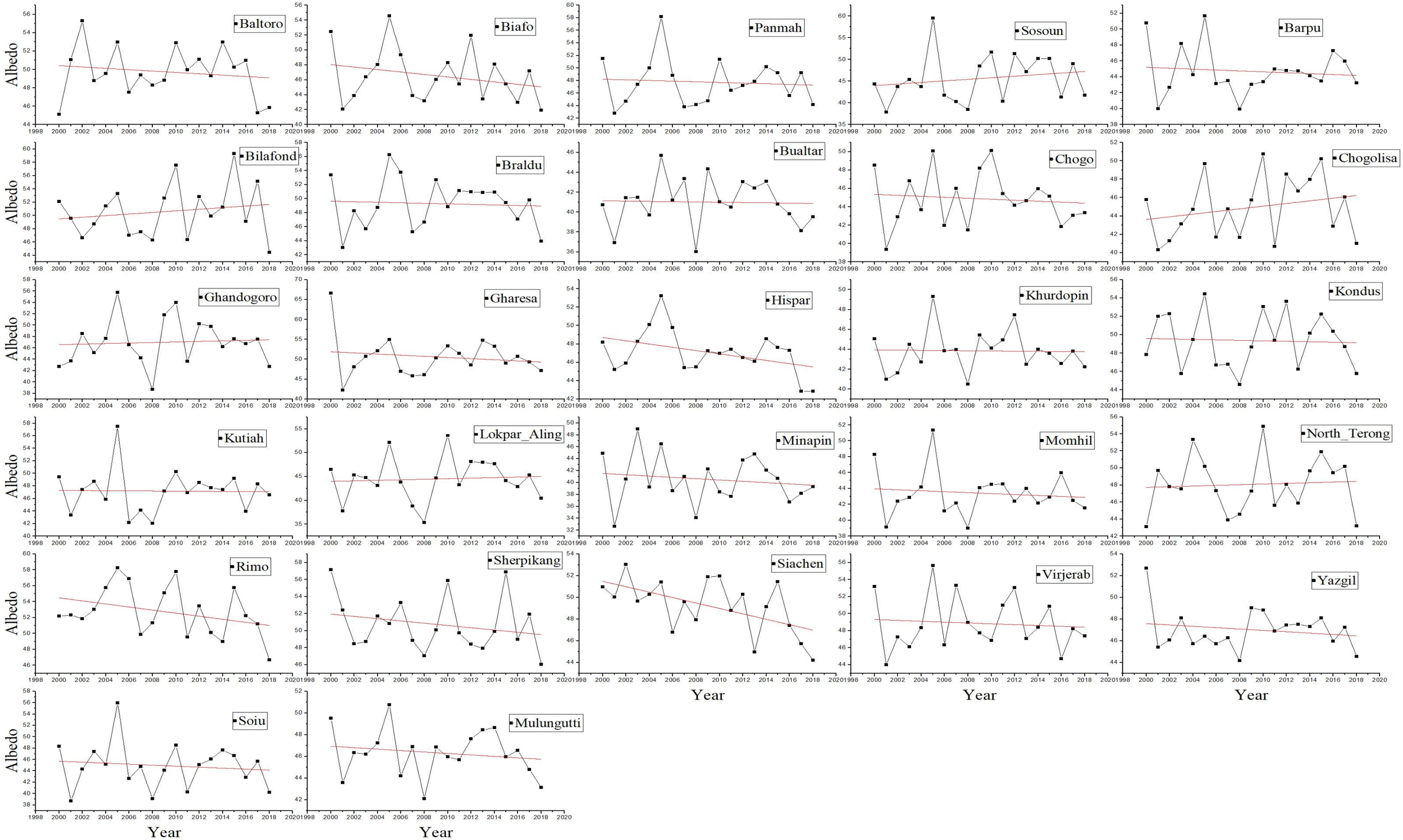

Figure 7. Graph showing trend of the variation in summer albedo for the glacier under the study from 2000 to 2018

Trend of the glacier surface albedo variation. The trend in the average albedo from 2000 to 2018 tended to decrease as we move from eastern part towards the north-western part of the Karakoram in Pakistan (Figure 8), as the study of Rankl, Kienholz and Braun [23] revealed that the glaciers are retreating towards the north-western part of the Karakoram. This decrease in albedo is due to the decrease in altitude towards the Hindu Kush region and is influenced by the reduced precipitation in the northern part of Karakoram compared to the central part of the Karakoram [32]. The highest albedo in the study area was observed on the Rimo Glacier (53.75%), and the trend decreased towards the Hindu Kush region. The lowest average albedo was observed at the Minapin Glacier (40.96%), which is the last glacier in the study area moving towards the Hindu Kush mountain region.

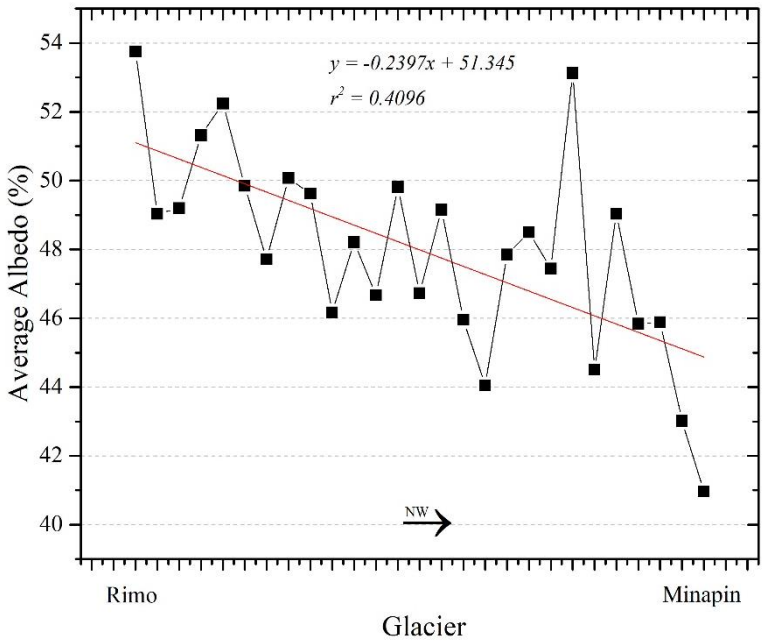

Figure 8. The direction of the decrease in albedo showing that the albedo is decreasing towards the north-western part of the Karakoram

Albedo difference between 2000 and 2018. A significant change in albedo was noticed between the year 2000 and 2018 throughout the Karakoram region under study (Figure 9). Highest albedo during the year 2000 was observed at Gharesa glacier (66.57%) and Rimo glacier (48.95%) which we encounter very first if we move towards north-western direction of the Karakoram region in Pakistan exhibit highest amount of albedo during 2018. There was different of about 17.62% surface albedo between the maximum amount of albedo of both year 2000 and 2018 at a single glacier. There was an average about 6 % decrease in the amount of albedo was observed between 2000 and 2018 throughout the study area. Almost all the glacier exhibits a decreasing trend in year 2018 from 2000 but an increasing trend was observed at Ghandogoro glacier which was not very significant (Figure 10).

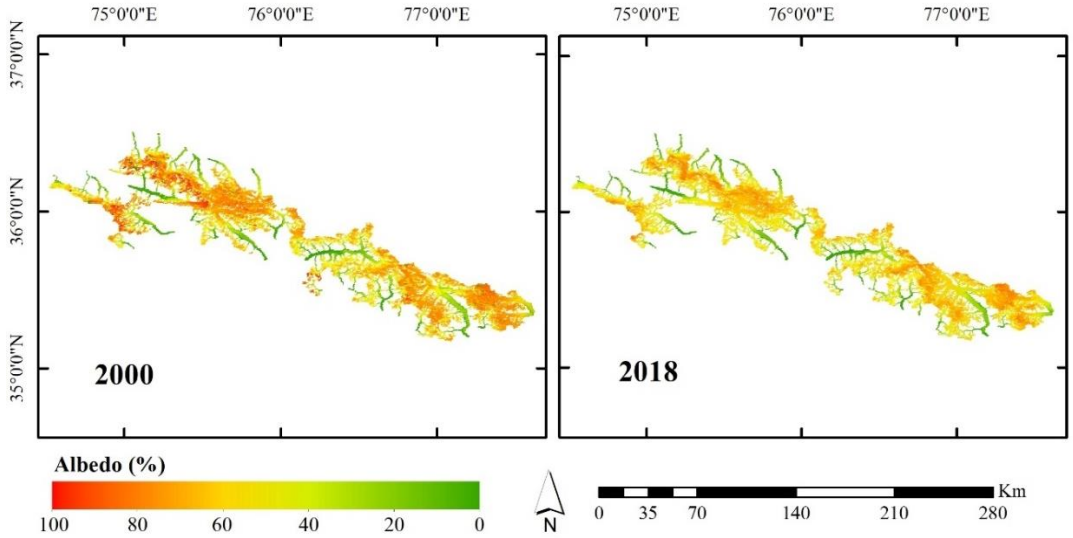

Figure 9. Albedo variation between year 2000 and 2018

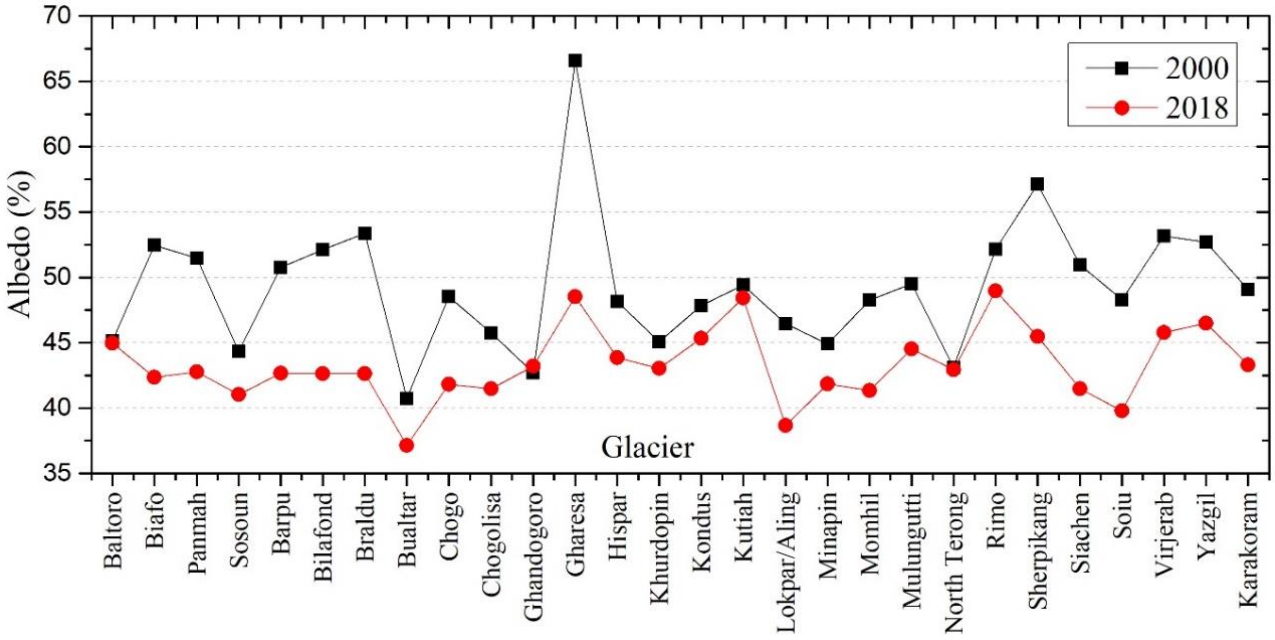

Figure 10. Graph showing albedo variation between the year 2000 and 2018. Black graph represents the albedo in year 2000 and red graph represent the albedo in year 2018.

Albedo Variations with Elevation. We divided the study area into six elevation zones: 2000-3000 m, 3000-4000 m, 4000-5000 m, 5000-6000 m, 6000-7000 m, and 7000-8000 m. Later, we resampled at a resolution of 500 m to compare it with the M(O/Y)D10A1 data. Then, we analysed the variations in albedo in the different elevation zones. The maximum albedo was observed in the elevation zone between 7000 and 8000 m, and the minimum albedo was observed in the elevation zone between 2000 and 3000 m during the time period between 2000 and 2018. Albedo increased as we move from low-elevation to high-elevation zones (Figure 11).

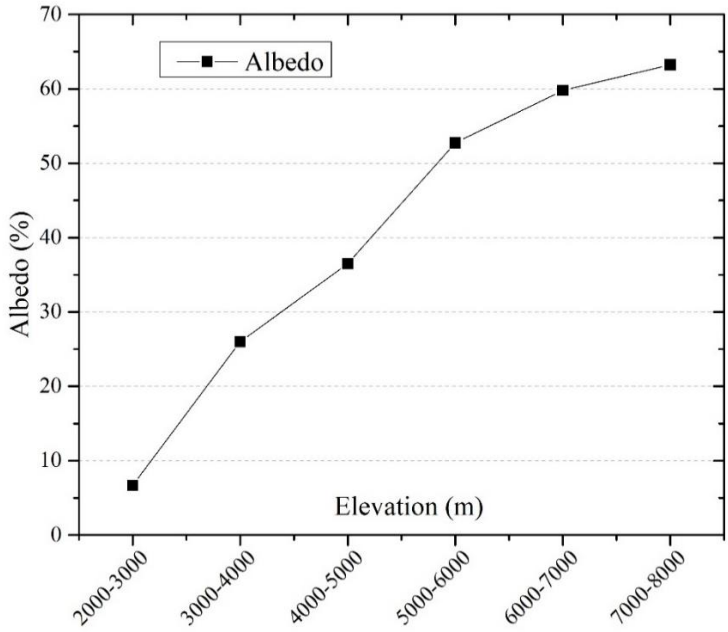

Figure 11. The amount of albedo increases with increasing elevation and as the temperature decreases, causing less glacial melt, which alternately increases the albedo moving towards areas with higher elevations.

The variations in albedo is very closely related to meteorological factors (i.e., precipitation and temperature) during the summer season. The weather station data were obtained for the Gilgit-Baltistan territory and then correlated with the MODIS-observed albedo data. Pearson correlation coefficient were used to quantify the correlations between the MODIS albedo data and the ground-based weather station data (Table 4).

Table 4. Pearson correlation coefficients between albedo and the meteorological factors

		Temperature	Precipitation
Albedo	Pearson Correlation	-.811**	.809**
	Sig. (2-tailed)	.002	.003

**. Correlation is significant at the 0.01 level (2-tailed).

A strong negative correlation was found between the temperature and MODIS albedo product. The relationship shows that the MODIS-observed albedo value during the summer season increases with decreasing temperature. The value of Pearson's *r* is -0.811, which indicates that the relationship between albedo and temperature at the Karakoram glaciers in the summer season is very strong and very significant at the 0.01 level (Figure 4). Under warmer conditions, the rate of metamorphism of snow grains ultimately increases, and due to snow melting, the rate of albedo retrieval decreases. Similarly, albedo is higher during cold climate conditions. The melting of snow grains leaves impurities behind, which absorb solar radiation, causing a decrease in albedo.

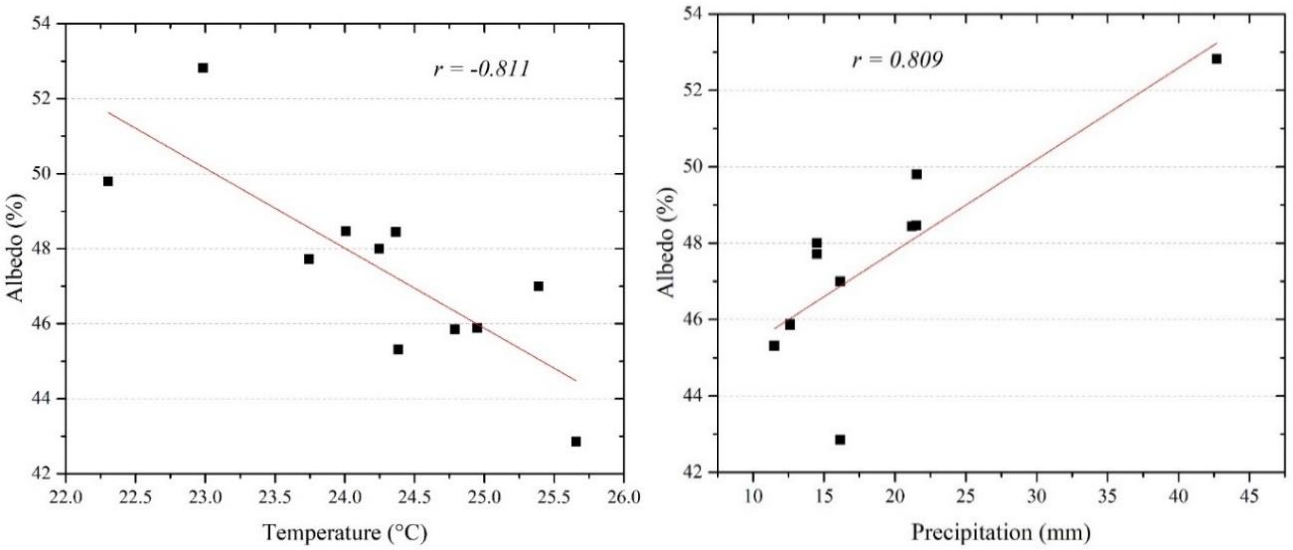

Figure 12. Correlation of surface albedo with temperature and precipitation. Albedo have a significant negative and significant positive correlation with temperature and precipitation respectively.

The relationship between albedo and precipitation was found to be very strong in the positive direction. The correlation shows that the value of albedo increases with increasing precipitation. The value of Pearson's r is 0.809, exhibiting a strong and significant correlation at the 0.01 level (Figure 12). The precipitation at the high altitudes in the Karakoram region is in the form of snowfall during the winter as well as the summer, which helps to buffer the glaciers against warming [33]. Gul, *et al.* [34] observed that the retreating glaciers in the Karakoram mountains in the northern part of Pakistan have a shown a significant negative correlation with the changing temperature in the region. The correlations between albedo and temperature and between albedo and precipitation during the summer season are expressed in Table 4.

Discussion.

The albedo value decreases during the summer season in the Karakoram glacial, which is situated in the Gilgit-Baltistan territory of Pakistan. There may be many reasons for this decrease in albedo. Global warming can be the main cause. According to the research conducted by Kapnick, *et al.* [35], global warming is not particularly effective in that region because of the unique seasonal cycle dominated by non-monsoonal precipitation, which protects it from the glacial reduction. Thus, our findings indicate that the large amount of precipitation in the study area shows a greater albedo response in the study area.

Bolch, *et al.* [36] studied that the behaviour in the Karakoram region is different from the other regions, as there is stability or gain in the mass compared to the Himalayas, where there is a rate of decrease in the glaciers similar to that in other parts of the world. Gardelle, Berthier and Arnaud conducted a study based on two different digital elevation models to calculate the mass balance of central Karakoram between 1999 and 2008 and found that there was a slight gain in the glacier mass balance in the early twenty-first century.

Climatic conditions are the potential sources affecting albedo retrieval. According to recent research conducted by Kumar, *et al.* [37], the rise in temperature and decline in the

precipitation had a massive impact on the glaciers in the Karakoram, resulting in the form of mass loss supporting our results of albedo decline. The mass loss was very low during 2000-2009; our results are quite similar in that the change in albedo retrieval (decline) was nominal during 2000-2009 compared to recent years. The trend in the darkening surface is due to the reduction in snow from enhanced glacier melting, which is likely reinforced by climatic factors, i.e., increasing temperature and decreasing precipitation [38]. The decrease in albedo appears to be the consequences of the changes in the climate, including reduced precipitation and an increase in the air temperature of glaciers in the Ortles-Cevedale group, Central Italian Alps [20] and Dongkemadi Glacier in China [18].

Conclusion.

The surface energy and mass balance of glaciers strongly depends on the amount of solar radiation absorbed at the surface, which is mainly controlled by glacier surface albedo. The present research was conducted using MODIS-derived daily snow albedo data to observe the spatial and temporal variations of surface albedo of glaciers in the Karakoram region of Pakistan. The research was focused on the spatiotemporal variations during the summer season (June, July and August) from year 2000 to 2018. After reprojection and resampling of data, MODIS aqua satellite data and MODIS terra satellite data was combined to eliminate the clouds effecting the surface albedo of glaciers. Study time period was divided into two spans i.e. Past decade (2000-2009) and recent years (2010-2018). The main purpose of this division was to elaborate the glacier change in recent years is quite significant than the past decade. Ground-based meteorological weather station data was collected from Pakistan Meteorological Department (PMD). Climate data was correlated with the satellite data to find out the relationship of glacier surface albedo with temperature and precipitation. The impact of climate change and LAI on glaciers darkening is discussed in details. Here are the main findings of the study:

- The overall average change in the amount of albedo from year 2000 to 2018 at Karakoram glaciers was found in decreasing direction. The change in decreasing albedo was observed at a rate of 0.04% per year throughout the study time period. The highest amount of albedo was observed 52.82% during year 2005 and the lowest average albedo in a single year was observed 42.85% during 2008. Few glaciers exhibited increase in the albedo but most of the glacier showed decreasing albedo trend. Approximately 77.78% of glaciers in the Karakoram region under study exhibited a decrease in albedo from year 2000 to 2018.
- The amount of albedo was observed highest at almost all the glaciers under study during year 2005, following high winter snowfall and lower summer temperature in this year. According to the several reports by NASA Earth Observatory, Pakistan Meteorological Department (PMD) and Pakistan National Media, heavy snowfall was occurred in northern part of Pakistan during winter season of year 2005, breaking the record of past three decades. Ground-based weather stations data showed minimum summer temperature during 2005 throughout the study time period.
- Albedo change during the last decade (2000-2009) and recent years (2010-2018) was monitored. It was observed that the change in albedo during past decade was found decreasing at a rate of 0.12% per year. The annual change in the amount of albedo was found at a decreasing rate of 0.45% during recent years. A significant change in

decreasing amount of albedo was observed as compared to the last decade at Karakoram glaciers.

- The difference in the amount of albedo was discussed between 2000 and 2018. Overall change in the average amount of albedo was observed ~6% in decreasing trend between 2000 and 2018 throughout the study area. The highest amount of average albedo for a single glacier during year 2000 was observed 66.57% at Gharesa glacier and during the year 2018 was observed 48.95% at Rimo glacier. A significant amount of change in highest albedo observed during 2000 and 2018 with a difference of 17.62% decrease in albedo in year 2018.
- The study area was divided into six elevation zones (2000-3000 m, 3000-4000 m, 4000-5000 m, 5000-6000 m, 6000-7000 m, and 7000-8000 m) and the albedo change in each zone was discussed separately. The lowest amount of albedo was observed 6.67% at lowest elevation zone (2000-3000m) and highest amount of average albedo was observed 63.22% at highest elevation zone (7000-8000m). The increase in the amount of albedo with increasing elevation is due to the low temperature and high precipitation at higher elevations.
- The direction of change in albedo was observed decreasing towards north-western direction towards Hindu-Kush mountain range. This decrease in the amount of albedo towards NW direction is because of decreasing altitude following low precipitation. Highest amount of albedo was observed at Rimo glacier which is at highest elevation among all the glaciers in the study region. While the lowest albedo was observed at Baultar glacier and Minapin glacier are at lowest elevation among all the glaciers in Karakoram study region.
- The albedo change in the study region is closely related to the climatic factors (precipitation and temperature). A strong positive correlation was observed between precipitation and surface albedo at 99% confidence level. While a strong negative correlation was observed between temperature and surface albedo at 99% confidence level.

Recommendations.

According to our findings, the decrease in albedo was very slight in the first decade, but the rate of decrease was higher during recent years throughout the whole Karakoram glacial region of Pakistan. The overall trend of albedo decrease was not very significant in Karakoram glacial region of Pakistan. As per our study based on MODIS data, there was a slight decrease or no change (for some glaciers) in the Karakoram region in Pakistan during the first decade of the 21st century, but later, the rate of the decrease in glacier albedo is higher as the amount of albedo observed is decreasing relatively fast during recent years. Although the overall average amount of decrease in albedo is very small, but it is not negligible. However, more extensive studies using high-resolution satellite data as well as ground-based station data considering the anthropogenic activities causing albedo changes are required.

REFRENCES

[1] "Global Climate Change, Melting Glaciers." https://www.nationalgeographic.com/environment/article/big-thaw (accessed Mar. 08, 2022).

[2] S. Kazlowski and T. Roosevelt, "The last polar bear : facing the truth of a warming world : a photographic journey," p. 207, 2008, Accessed: Mar. 08, 2022. [Online]. Available: https://books.google.com/books/about/The_Last_Polar_Bear.html?hl=ca&id=62n0oNyN5Q0C.

[3] K. Casey, "The coming chaos : fossil fuel depletion and global warming," p. 208.

[4] "Randolph Glacier Inventory-A Dataset of Global Glacier Outlines: Version 6.0," 2017.

[5] D. Farinotti *et al.*, "A consensus estimate for the ice thickness distribution of all glaciers on Earth," *Nat. Geosci.*, vol. 12, no. 3, pp. 168–173, Mar. 2019, doi: 10.1038/S41561-019-0300-3.

[6] R. L. Armstrong *et al.*, "Runoff from glacier ice and seasonal snow in High Asia: separating melt water sources in river flow," *Reg. Environ. Chang.*, vol. 19, no. 5, pp. 1249–1261, Jun. 2019, doi: 10.1007/S10113-018-1429-0/FIGURES/6.

[7] M. Huss and R. Hock, "Global-scale hydrological response to future glacier mass loss," *Nat. Clim. Chang.*, vol. 8, no. 2, pp. 135–140, Feb. 2018, doi: 10.1038/S41558-017-0049-X.

[8] N. Forsythe, C. G. Kilsby, H. J. Fowler, and D. R. Archer, "Assessment of Runoff Sensitivity in the Upper Indus Basin to Interannual Climate Variability and Potential Change Using MODIS Satellite Data Products," *https://doi.org/10.1659/MRD-JOURNAL-D-11-00027.1*, vol. 32, no. 1, pp. 16–29, Feb. 2012, doi: 10.1659/MRD-JOURNAL-D-11-00027.1.

[9] S. G. Warren, "Optical properties of snow," *Rev. Geophys.*, vol. 20, no. 1, pp. 67–89, Feb. 1982, doi: 10.1029/RG020I001P00067.

[10] J. Stroeve, J. E. Box, F. Gao, S. Liang, A. Nolin, and C. Schaaf, "Accuracy assessment of the MODIS 16-day albedo product for snow: comparisons with Greenland in situ measurements," doi: 10.1016/j.rse.2004.09.001.

[11] R. E. Dickinson, "Land Surface Processes and Climate—Surface Albedos and Energy Balance," *Adv. Geophys.*, vol. 25, no. C, pp. 305–353, Jan. 1983, doi: 10.1016/S0065-2687(08)60176-4.

[12] A. W. Nolin and J. Stroeve, "The changing albedo of the Greenland ice sheet: implications for climate modeling," *Ann. Glaciol.*, vol. 25, pp. 51–57, 1997, doi: 10.3189/S0260305500013793.

[13] D. Fugazza, A. Senese, R. S. Azzoni, M. Maugeri, and G. A. Diolaiuti, "Spatial distribution of surface albedo at the Forni Glacier (Stelvio National Park, Central Italian Alps)," *Cold Reg. Sci. Technol.*, vol. 125, pp. 128–137, May 2016, doi: 10.1016/J.COLDREGIONS.2016.02.006.

[14] F. P. J. Valero and R. J. Charlson, "Albedo-watching satellite needed to monitor change," *Nat. 2008 4517181*, vol. 451, no. 7181, pp. 887–887, Feb. 2008, doi: 10.1038/451887c.

[15] D. Six, P. Wagnon, J. E. Sicart, and C. Vincent, "Meteorological controls on snow

and ice ablation for two contrasting months on Glacier de Saint-Sorlin, France," *Ann. Glaciol.*, vol. 50, no. 50, pp. 66–72, 2009, doi: 10.3189/172756409787769537.

[16] T. C. Grenfell and D. K. Perovich, "Seasonal and spatial evolution of albedo in a snow-ice-land-ocean environment," *J. Geophys. Res. Ocean.*, vol. 109, no. C1, p. 1001, Jan. 2004, doi: 10.1029/2003JC001866.

[17] J. K. Malmros, S. H. Mernild, R. Wilson, T. Tagesson, and R. Fensholt, "Snow cover and snow albedo changes in the central Andes of Chile and Argentina from daily MODIS observations (2000–2016)," *Remote Sens. Environ.*, vol. 209, pp. 240–252, May 2018, doi: 10.1016/J.RSE.2018.02.072.

[18] X. Yue *et al.*, "Spatial and temporal variations of the surface albedo and other factors influencing Urumqi Glacier No. 1 in Tien Shan, China," *J. Glaciol.*, vol. 63, no. 241, pp. 899–911, 2017, doi: 10.1017/jog.2017.57.

[19] B. W. Brock, I. C. Willis, and M. J. Sharp, "Measurement and parameterization of albedo variations at Haut Glacier d'Arolla, Switzerland," *J. Glaciol.*, vol. 46, no. 155, pp. 675–688, 2000, doi: 10.3189/172756500781832675.

[20] D. Fugazza, A. Senese, R. S. Azzoni, M. Maugeri, D. Maragno, and G. A. Diolaiuti, "New evidence of glacier darkening in the Ortles-Cevedale group from Landsat observations," *Glob. Planet. Change*, vol. 178, pp. 35–45, 2019, doi: 10.1016/j.gloplacha.2019.04.014.

[21] J. F. Calleja, A. Corbea-Pérez, S. Fernández, C. Recondo, J. Peón, and M. Ángel De Pablo, "Snow Albedo Seasonality and Trend from MODIS Sensor and Ground Data at Johnsons Glacier, Livingston Island, Maritime Antarctica," *Sensors 2019, Vol. 19, Page 3569*, vol. 19, no. 16, p. 3569, Aug. 2019, doi: 10.3390/S19163569.

[22] M. J. Butt, M. E. Assiri, A. Waqas, M. J. Butt, M. E. Assiri, and A. Waqas, "Spectral Albedo Estimation of Snow Covers in Pakistan Using Landsat Data," *ESE*, vol. 3, no. 2, p. 104, Aug. 2019, doi: 10.1007/S41748-019-00104-1.

[23] H. MacHguth and M. Huss, "The length of the world's glaciers a new approach for the global calculation of center lines," *Cryosphere*, vol. 8, no. 5, pp. 1741–1755, Sep. 2014, doi: 10.5194/TC-8-1741-2014.

[24] W. T. Pfeffer *et al.*, "The Randolph Glacier Inventory: a globally complete inventory of glaciers," *J. Glaciol.*, vol. 60, no. 221, pp. 537–552, 2014, doi: 10.3189/2014JOG13J176.

[25] M. Rankl, C. Kienholz, and M. Braun, "Glacier changes in the Karakoram region mapped by multimission satellite imagery," *Cryosphere*, vol. 8, no. 3, pp. 977–989, May 2014, doi: 10.5194/TC-8-977-2014.

[26] K. Hewitt, "Glaciers of the Karakoram Himalaya," 2014, doi: 10.1007/978-94-007-6311-1.

[27] Y. B. Seong *et al.*, "Quaternary glacial history of the Central Karakoram," *Quat. Sci. Rev.*, vol. 26, pp. 3384–3405, 2007, doi: 10.1016/j.quascirev.2007.09.015.

[28] G. A. Riggs, D. K. Hall, and M. O. Román, "MODIS Snow Products Collection 6 User Guide," 2016.

[29] A. G. Klein and J. Stroeve, "Development and validation of a snow albedo algorithm for the MODIS instrument," *Ann. Glaciol.*, vol. 34, pp. 45–52, 2002, doi: 10.3189/172756402781817662.

[30] J. C. Stroeve, J. E. Box, and T. Haran, "Evaluation of the MODIS (MOD10A1) daily

snow albedo product over the Greenland ice sheet," *Remote Sens. Environ.*, vol. 105, no. 2, pp. 155–171, Nov. 2006, doi: 10.1016/J.RSE.2006.06.009.

[31] H. Xie, X. Wang, and T. Liang, "Development and assessment of combined Terra and Aqua snow cover products in Colorado Plateau, USA and northern Xinjiang, China," *https://doi.org/10.1117/1.3265996*, vol. 3, no. 1, p. 033559, Oct. 2009, doi: 10.1117/1.3265996.

[32] S. Weiers, "Zur Klimatologie des NW-Karakorum und angrenzender Gebiete statistische Analysen unter Einbeziehung von Wettersatellitenbildern und eines Geographischen Informationssystems (GIS) ; mit 33 Tabellen."

[33] D. Scherler, B. Bookhagen, M. R. Strecker, D. Scherler, B. Bookhagen, and M. R. Strecker, "Spatially variable response of Himalayan glaciers to climate change affected by debris cover," *NatGe*, vol. 4, no. 3, pp. 156–159, Mar. 2011, doi: 10.1038/NGEO1068.

[34] C. Gul, S. chang Kang, B. Ghauri, M. Haq, S. Muhammad, and S. Ali, "Using Landsat images to monitor changes in the snow-covered area of selected glaciers in northern Pakistan," *J. Mt. Sci.*, vol. 14, no. 10, pp. 2013–2027, Oct. 2017, doi: 10.1007/S11629-016-4097-X.

[35] S. B. Kapnick, T. L. Delworth, M. Ashfaq, S. Malyshev, and P. C. D. Milly, "Snowfall less sensitive to warming in Karakoram than in Himalayas due to a unique seasonal cycle," *Nat. Geosci.*, vol. 7, no. 11, pp. 834–840, Nov. 2014, doi: 10.1038/NGEO2269.

[36] T. Bolch *et al.*, "The state and fate of Himalayan glaciers," *Science*, vol. 336, no. 6079, pp. 310–314, Apr. 2012, doi: 10.1126/SCIENCE.1215828.

[37] A. Kumar, H. S. Negi, K. Kumar, C. Shekhar, and N. Kanda, "Quantifying mass balance of East-Karakoram glaciers using geodetic technique," *Polar Sci.*, vol. 19, pp. 24–39, Mar. 2019, doi: 10.1016/J.POLAR.2018.11.005.

[38] N. Forsythe, H. J. Fowler, X. Li, S. Blenkinsop, and D. Pritchard, "Forsythe N , Fowler HJ , Li XF , Blenkinsop S , Pritchard D . Karakoram temperature and glacial melt driven by regional atmospheric circulation variability . Nature Climate Change 2017 ," no. February, 2018.

Copyright © by authors and 50Sea. This work is licensed under Creative Commons Attribution 4.0 International License.